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Availability of Rare-Earth, Yttrium, and Related Thorium Oxides—Market Economy Countries

A Minerals Availability Appraisal

By T. F. Anstett

UNITED STATES DEPARTMENT OF THE INTERIOR

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Donald Paul Hodel, Secretary

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As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environment and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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PREFACE

The Bureau of Mines is assessing the worldwide availability of selected minerals of economic signficance, most of which are also critical minerals. The Bureau identifies, collects, compiles, and evaluates information on producing, developing, and explored deposits, and mineral processing plants worldwide. Objectives are to classify both domestic and foreign resources, to identify by cost evaluation those demonstrated resources that are reserves, and to prepare analyses of mineral availability.

This report is one of a continuing series of reports that analyze the availability of minerals from domestic and foreign sources. Questions about, or comments on, these reports should be addressed to Chief, Division of Minerals Availability, Bureau of Mines, 2401 E St., N.W., Washington, DC 20241.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

km	kilometer	mt	metric ton
m	meter	mt/h	metric ton per hour
mm	millimeter	mt/yr	metric ton per year
yr	year	yr	year

AVAILABILITY OF RARE-EARTH, YTTRIUM, AND RELATED THORIUM OXIDES—MARKET ECONOMY COUNTRIES

A Minerals Availability Appraisal

By T. F. Anstett[1]

ABSTRACT

The Bureau of Mines estimated the potential availability of rare-earth oxides (REO), including yttrium, and thorium, which is also contained in the rare-earth bearing minerals monazite and bastnasite, from 38 properties in market economy countries (MEC's). Only nine of the properties evaluated produce or would produce REO as the primary product; the others contain REO as a byproduct, chiefly from mineral sands operations recovering rutile, ilmenite, and zircon.

Nearly 77% (2,578,000 mt) of the total 3,355,000 mt of recoverable REO evaluated is from producing properties. It is estimated that 21% (705,000 mt) of this total is from properties that could not realize a positive rate of return at the January 1984 market prices for the recovered commodities.

At production capacities assumed for this evaluation, the amount of REO potentially available from producers ranges from an estimated 46,500 mt in 1986, to a peak of 50,900 mt in 1992, to 49,900 mt by the year 2000. Total MEC production in 1984 was estimated at 40,700 mt. Assuming demand does not increase sharply, producing properties can continue to fulfill overall REO demand through at least the end of this century.

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INTRODUCTION

The Bureau of Mines investigated the potential availability of the rare earths, a group of chemically related commodities having important industrial applications. This report addresses the availability of rare-earth oxides (REO) (and yttrium oxide) in concentrate from 29 foreign and 9 domestic properties. The amount of thorium contained in monazite, an important thorium source material, was also estimated. Detailed information concerning domestic thorium resources and processing methods and costs is contained in other publications (*1-2*).[2]

Unlike that of most mineral commodities, world production of rare earths is dominated by one mine, Mountain Pass, CA, which typically accounts for about half of annual world production. Mountain Pass is also the only MEC operation that produces the mineral bastnasite as a primary product. Nearly all of the remaining MEC production of rare earths is from the mineral monazite, a byproduct of processing mineral sands for the titanium minerals, rutile and ilmenite, and for the zirconium mineral, zircon.

Domestic properties were evaluated by personnel of the Bureau's Field Operations Centers, and foreign data collection and cost estimation were performed under contract by Pincock, Allen and Holt Inc., Tucson, AZ; personnel of the Bureau's Minerals Availability Field Office, Denver, CO, evaluated the data and performed the economic analyses.

[2]Italic numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

METHODOLOGY

Because of the byproduct nature of a large percentage of world rare-earth production, and the fact that the rare-earth-bearing mineral monazite is produced as an integral part of the recovery process of the titanium minerals (rutile and ilmenite), the most practical investigative approach to assess rare-earth availability is in terms of its availability as a function of overall profitability of the properties evaluated. Consequently, availability results are presented as a function of a measure of profitability of each property, as indicated by its discounted-cash-flow rate of return (DCFROR), defined as the rate of return that makes the present worth of cash flows from an investment equal to the present worth of all after-tax investments (*3*). A 0% DCFROR is commonly considered as the "breakeven" point for an operation.

An outline of the evaluation procedure followed for this study is shown in figure 1. The analysis methodology is as follows:

1. The quantity and grade of rare-earth resources were evaluated in relation to physical and technological conditions that affect production from each property as of the study date, January 1984.
2. Appropriate mining and processing methods were determined for producing operations and proposed for undeveloped properties. Related capital and operating costs to process material to a marketable concentrate were estimated. Operating costs include transportation to deliver concentrates to port or process plant. It was assumed that all operations were 100% equity financed.
3. An economic analysis of each operation was performed to determine the DCFROR. Revenues generated for each property's cash flow were based on January 1984 prices of commodities that are or could be produced at each property.
4. All properties were aggregated onto total and annual availability tables and curves, which show the amount of recoverable rare earths, in terms of REO, potentially available at various DCFROR's. Availability of the individual rare earths (as REO), yttrium (as Y_2O_3), and thorium (as ThO_2), are also shown.

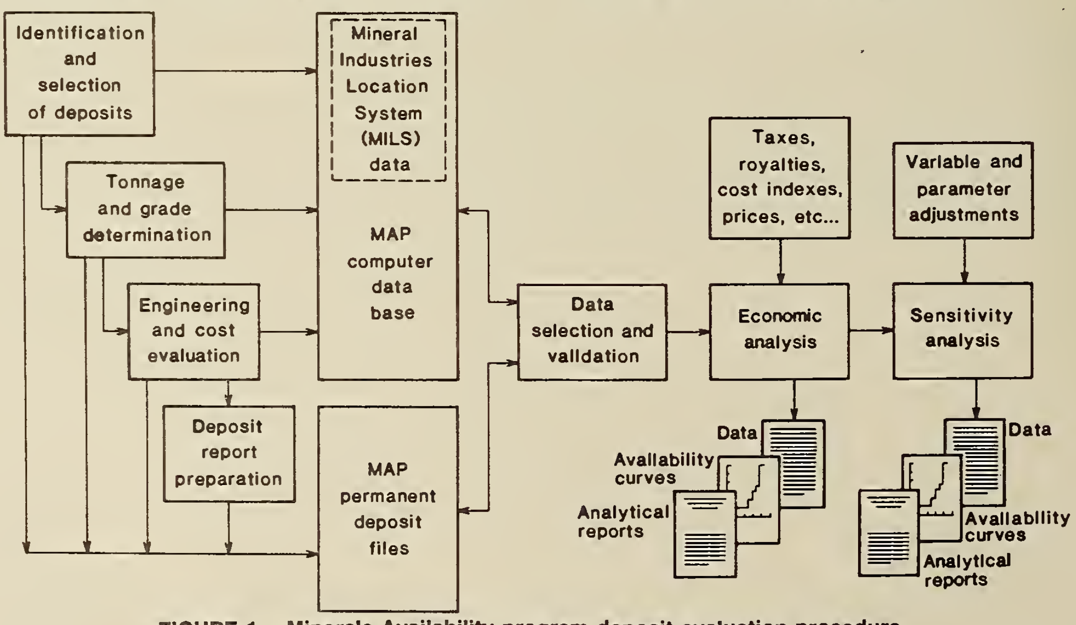

FIGURE 1.—Minerals Availability program deposit evaluation procedure.

REO CHARACTERISTICS AND USES

The rare-earth elements, or lanthanides, are 15 chemically similar elements with atomic numbers 57–71. They are lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium thulium, ytterbium, and lutetium. Promethium, a fission product of uranium, has no known naturally occurring stable isotopes. Although not a member of the lanthanide series, yttrium (atomic number 39) is grouped with the rare-earth elements because it typically occurs with them in nature and has similar chemical properties.

The rare-earth elements have been classified into two general groups: the light or cerium subgroup, comprising the first seven elements listed above (atomic numbers 57–63); and the heavy or yttrium subgroup, comprising the elements with atomic numbers 64–71 as well as yttrium. Despite its low atomic weight, yttrium is categorized with the heavy rare earths because its occurence, ionic radius, and behavioral properties are closer to those of the heavier rare-earth elements than to the lighter group.

Important industrial applications of the rare earths include: petroleum cracking catalysts; metallurgical (including iron and steel additives, alloys, and mischmetal); ceramics and glass (including polishing compounds and glass additives); and miscellaneous, including phosphors, electronics, nuclear energy, lighting, and research. Among these general use categories, petroleum catalysts accounted for 65% of U.S. consumption in 1982, metallurgical uses accounted for 20%, and ceramics and glass accounted for 12%; miscellaneous uses accounted for 3% (*4*).

One of the most important applications of rare earths is in catalytic activities. Mixtures of lanthanum, neodymium, and praseodymium chlorides are used in catalysts for petroleum refining. Between 1% and 5% rare-earth chloride is added to zeolite catalysts to increase their efficiency in the conversion of crude oil to petroleum products. The demand for rare-earth chlorides for cracking catalysts is on the increase, and it is believed that more companies will become involved in their production in the future (*5*, p. 34).

Mischmetal, produced by the electrolysis of anhydrous mixed rare-earth chlorides, has applications in the iron and steel and the lighter flint industries. In the iron and steel industry, the physical and rolling properties of the metal are improved by the use of mischmetal. Rare-earth treated, high-strength, low-alloy steels are being increasingly used in the automobile industry as structural components and in lightweight sheet applications (*6*, p. 740.)

Rare-earth metals such as cerium, praseodymium, neodymium, samarium, dysprosium, and mischmetal are used in the manufacture of permanent magnets. These magnets, which are stronger than other magnets, are used in electric wristwatches, tachometers, traveling wave tubes, line printers, and electric motors and generators (*6*, p. 742). The most powerful magnets known are made from neodymium plus iron and boron. The rapidly growing rare-earth permanent magnet business is estimated to be worth $100 million annually (*7*).

The energy concerns of the 1970's spurred development of more efficient automobile engines, experimental models of which require the use of yttria-stabilized zirconia for elevated temperature applications, and development of lanthanum-nickel intermetallics for solid-state hydrogen storage and processing. Rare-earth compounds are also used in the glass industry in a variety of applications including polishing, decolorizing, and the manufacture of special glasses.

GEOLOGY AND MINERALOGY

The rare-earth elements and yttrium are essential constituents in more than 100 minerals; however, only a few minerals occur in sufficient concentration to qualify as ore. Monazite, bastnasite, and xenotime are the most important rare-earth-bearing ore minerals. Monazite, a rare-earth phosphate, can contain approximately 70% combined REO, including 2% Y_2O_3. Most monazite concentrates range from 55% to 65% contained REO. Table 1 shows average concentrations of the various REOs in the important ore minerals.

Bastnasite, a fluorocarbonate mineral, can contain approximately 75% REO and very minor amounts of Y_2O_3 (0.1%). Bastnasite flotation concentrates average approximately 60% REO, but the concentrate can be upgraded to 70% REO by acid leaching and to 85% REO by a combination of leaching and calcining. Molycorp Inc., the world's largest producer of bastnasite from its Mountain Pass property in California, produces bastnasite concentrate at all three grades.

Xenotime, an yttrium phosphate mineral, is found in the same geological environment as monazite and is a major source of yttrium. Among world rare-earth occurrences, those of China and Malaysia are the most significant source of yttrium-bearing xenotime, which is produced as a byproduct of tin placer mining.

Among other commercial mineral sources of rare earths and yttrium are apatite and multiple-oxide minerals such as euxenite and loparite. Although these minerals are mined for their REO content and constitute a substantial resource, they presently account for a comparatively minor percentage of REO production.

Table 1.—Individual REO contained in major source minerals (*5*, p. 19)
(Percent of total REO)

Oxide	Monazite	Bastnasite	Xenotime
Y_2O_3	2	0.1	60
La_2O_3	23	32	
CeO_2	46	50	
Pr_6O_{11}	5	4	10.6
Nd_2O_3	19	13	
Sm_2O_3	3	.5	1.2
Eu_2O_3	.1	.1	.01
Gd_2O_3	1.7	.15	3.6
Tb_4O_7	.16	0	1
Dy_2O_3	.5	0	7.5
Ho_2O_3	.09	0	2
Er_2O_3	.13	0	6.2
Tm_2O_3	.01	0	1.27
Yb_2O_3	.06	0	6
Lu_2O_3	.006	0	.63

NOTE.—Columns do not total 100% because of independent rounding.

Heavy mineral sands occurring in modern placer deposits are the major source of monazite; the mineral normally is produced only as a byproduct of rutile, ilmenite, and zircon mining. The placers are formed by the natural processes of weathering, transportation, and concentration at a site of accumulation of heavy minerals whose origin is a primary source rock. Beach deposits are the most significant commercial placers. The largest accumulations exist where a coastline is indented and the beach is gently sloping. Important deposits of this type occur in Australia, India, Brazil, the Republic of South Africa, and the United States. Similar deposits occur in southeast Asia, where small amounts of xenotime are recovered as a byproduct of tin mining.

An important source of REO is carbonatite deposits, igneous assemblages of primarily carbonate minerals occurring as intrusions associated with undersaturated alkali igneous complexes formed along major rift zones. The most significant commercial carbonatite complex is at Mountain Pass, CA, which supplies much of the world's bastnasite and accounts for nearly half of the world's annual REO production and more than 60% of MEC production. Another important world bastnasite deposit is Baiyen-ebo in the Nei Monggol Autonomous Region of China. Other carbonatite complexes, such as Palabora in the Republic of South Africa, are known to contain large amounts of REO-bearing minerals, but none has produced commercially significant quantities on a sustained basis.

REO PRODUCTION AND DEMAND

WORLD PRODUCTION

Estimated production of REO from major world producers for the years 1981–84 is shown in table 2. The United States is the world's leading supplier of REO, almost all of which is from Molycorp Inc.'s Mountain Pass, CA, bastnasite operation; the United States also produces a small amount of REO from monazite annually. Table 2 includes U.S. bastnasite production only. Australia is the world's leading producer of monazite, as a byproduct of heavy mineral sands (chiefly ilmenite, rutile, and zircon) mining. Because of its byproduct status, Australian monazite production depends upon its relatively low and extremely variable composition in the heavy mineral sands, and the economics of the marginal cost of recovering monazite.

Australian monazite and xenotime producers presently sell all of their production. The country has no processing facilities beyond initial beneficiation, and the monazite concentrate is generally exported to the United States and Europe (mainly France) for processing. Exports have increased steadily during the past few years.

A particular problem relative to monazite concentrate marketing is the presence of radioactive thorium that typically occurs in monazite, generally in amounts on the order of 6% to 7% ThO_2. Currently, there is only limited demand for thorium, and its presence in monazite concentrates is generally regarded as a nuisance because safeguards must be taken and regulatory standards maintained while handling the material. Brazil and India do not allow the export of monazite because of its thorium content and are stockpiling thorium for possible future use as a nuclear fuel (energy source). Consequently, both countries have integrated operations that separate the rare-earth metals and thorium prior to export of the rare earths. NUCLEMON, a Brazilian Government-owned entity, mines heavy minerals sand chiefly for its monazite (thorium) content. From a revenue perspective, the monazite would be considered a byproduct of ilmenite and rutile production.

Probably the most significant recent development in REO production is the emergence of China as the world's third largest producer, after the United States and Australia. The country is believed to possess the world's largest REO reserves (*5*, p. 23). The Bureau of Mines estimates China's reserve base at 38 million mt REO, or nearly 80% of the total world reserve base (*8*). Annual production figures are not available for China, but 1985 production was estimated to be about 10,000 mt REO.

Table 2.—World mine production of REO, 1981–84 (*8*)
(Metric tons)

Country	1981	1982	1983	1984
MEC:				
Australia	7,430	5,229	7,975	9,189
Brazil	1,452	1,061	1,100	1,100
India	2,201	4,000	2,200	2,200
Malaysia	165	320	187	2,563
Thailand	84	59	77	172
United States[1]	17,094	17,501	17,083	25,311
Other	109	167	165	170
Total MEC	28,535	28,337	28,787	40,705
CPEC[2]:				
China	NA	NA	6,000	8,000
Other	NA	NA	1,500	1,500
World total[3]	NA	NA	36,000	50,000

NA Not available.
[1]Includes bastnasite production only.
[2]Centrally planned economy countries.
[3]Rounded.

DEMAND OUTLOOK

The solvent extraction technology, perfected in the 1960's for europium and yttrium oxides, has been expanded to commercial-scale separation and purification of at least 11 of the 15 rare-earth elements occurring in bastnasite, monazite, and xenotime. Most rare earths presently used by industry are consumed in the form of compounds containing special mixtures of rare-earth elements. On a percentage basis, the use of compounds is decreasing in favor of specific "mixes" for various end uses. Demand for separated and often high-purity rare earths has increased in recent years, and this trend is expected to continue.

One of the major developments in the rare-earths industry is the increasing number of uses for neodymium, which is in strong demand for lasers and magnets. While the future availability of this element could be a matter of concern given its increasing demand, neodymium is the third most abundant of the rare-earth elements and should be available in sufficient quantities to satisfy all expected demand. Shortages could occur because of the processors' need to balance the output of the commercially important rare-earth elements to operate profitably (*5*, p. 36).

Presently, a shortage in samarium is being experienced because processors do not have sufficient capacity. The demand for the heavy rare earths, including yttrium, has increased greatly for use in a variety of high-technology applications. Demand is particularly strong in Japan. The large demand for yttrium used in lasers and phosphors is

one factor that has prompted recent increases in the price of xenotime. Another market that is presently experiencing short supply is rare-earth chlorides; the strong demand is likely to continue (*5*, p. 36).

Traditional markets for mischmetal, a natural alloy of several of the rare earths, are the iron and steel and lighter flint industries. The iron and steel industry has been adversely affected by the economic recession of the early 1980's. Additionally, recent advances in technology have reduced the requirement for mischmetal, and demand levels for the material are not likely to return to pre-1982 levels.

Presently, most of the heavy rare earths derived from monazite processing are in high demand. Yttrium concentrate, because of its relatively high yttrium content (60% Y_2O_3) and high content of other heavy rare earths, is also in great demand. Xenotime is not as readily available as monazite, primarily because it is not as abundant and occurs in fewer commercial deposits.

REO RESOURCES IN EVALUATED PROPERTIES

A total of 38 properties were evaluated for this study. Evaluation of each property was performed on resource values sufficiently defined to be considered demonstrated according to the definitions established by the Bureau of Mines and U.S. Geological Survey (*9*) (fig. 2). Resource estimates for properties were available from published data, company personnel, and/or others familiar with the property.

A general description of individual properties evaluated is included in the appendix. Table 3 contains pertinent information for the 38 evaluated properties. Table 4 and figure 3 present a summary of demonstrated resources, by country and property status.

Of the 38 properties evaluated, only 9 produce or can produce rare earths as the primary product. Included in the nine properties are five in Brazil that, from a revenue standpoint, may be considered to be titanium properties, but are or could be mined primarily for their monazite content. All remaining properties evaluated can or could produce rare earths as a byproduct, primarily of processing titanium. The three Elliot Lake (Canada) properties, all producers of uranium, could recover rare earths as a byproduct by solvent extraction from a barren uranium solution. These three properties, plus the Silica Mine in Tennessee and Richards Bay in the Republic of South Africa, are producers that presently do not recover rare earths.

The total amount of REO potentially available annually from the 17 producers evaluated is nearly 50,000 mt at production capacities of those properties. Of the countries whose annual production is shown in table 2, only Malaysian and Thai producers have been excluded from this evaluation because of a paucity of rare-earth resource data for those properties at the time of this evaluation. However, these countries produced about 2,500 mt REO in 1984 (table 2).

Producing properties that recover rare earths as a byproduct of titanium processing account for 961,000 mt recoverable REO, or 29% of the total recoverable REO in all properties evaluated. Nonproducing properties that could recover rare earths as a byproduct of titanium mining con-

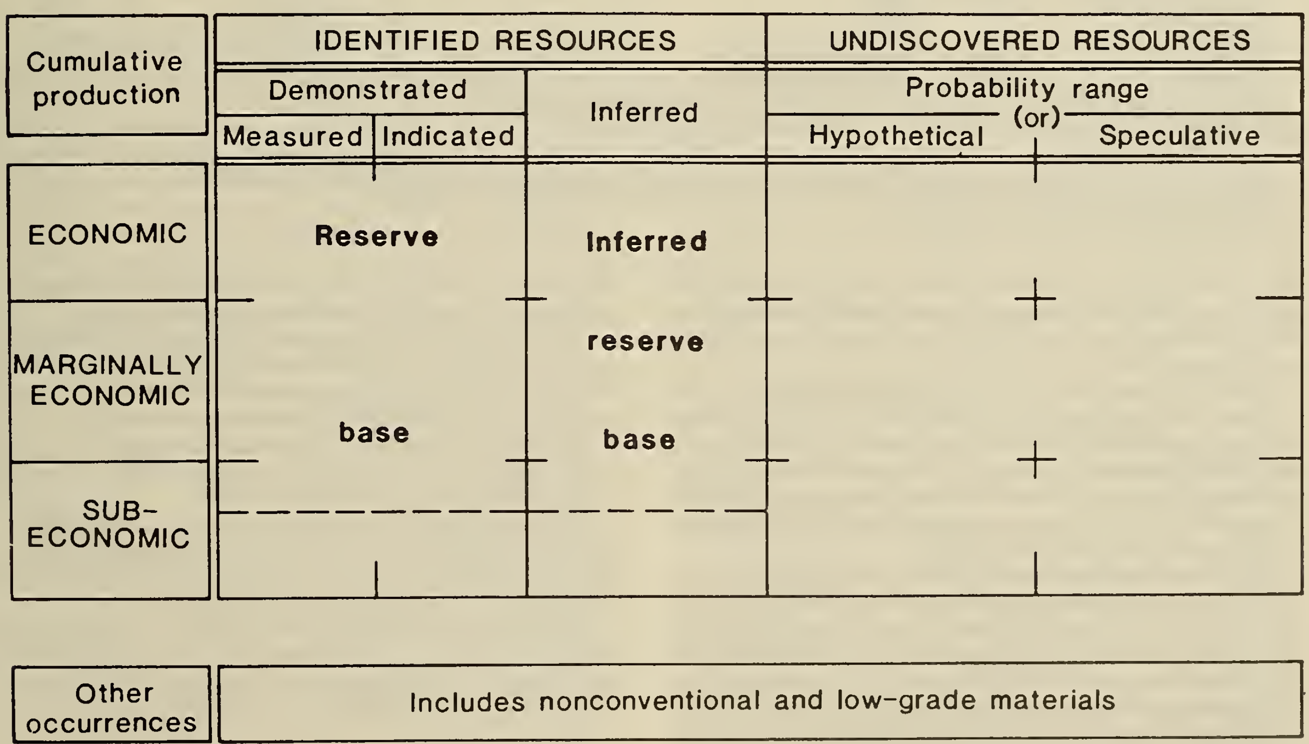

FIGURE 2.—Mineral resource classification categories.

Table 3.—Ownership and status of evaluated REO properties

Property[1]	Status[2]	Owner	Deposit[3] type	Mining method	Products[4]
Australia:					
Allied Eneabba	P	Allied Eneabba Ltd.	Pl	Strip level	R, I, L, Z, RE
Cable Sands	P	Cable Sands Pty. Ltd.	Pl	Dredge	I, R, Z, RE
Capel	P	Associated Minerals Consolidated Ltd. (AMC).	Pl	..do	I, R, L, SR, RE
Cataby	Exp	Metals Exploration, Alliance	Pl	..do	IR, I, Z, RE
Cooloola	PP	State of Queensland, Australian government	Pl	..do	R, I, Z, RE
Eneabba	P	AMC	Pl	Strip level	I, R, L, SR, RE
Fraser Island	PP	Murphyores, Dillingham	Pl	Dredge	R, I, Z, RE
Jurien Bay-Cooljarloo	PP	Western Mining Corp.	Pl	Strip level	R, I, L, Z, RE
Munmorah	PP	AMC	Pl	Dredge	R, I, Z, RE
North Capel	P	State of Western Australia	Pl	Strip level	I, R, L, Z, RE
North Stradbroke (AMC)	P	AMC	Pl	Dredge	R, I, Z, RE
North Stradbroke (CRL)	P	Consolidated Rutile Ltd.	Pl	..do	R, I, Z, RE
Yoganup Extended	P	Westralian Sands Ltd.	Pl	Open pit	I, R, L, Z, RE
Brazil:					
Alcobaca*	Exp	Brazilian Government	Pl	..do	RE, I, Z, R
Anchieta*	P	..do	Pl	..do	RE, I, Z, R
Aracruz*	Exp	..do	Pl	..do	RE, I, Z, R
Buena*	P	..do	Pl	..do	RE, I, Z, R
Serra*	Exp	..do	Pl	..do	RE, I, Z, R
Canada: Elliot Lake:					
Denison	P[5]	Denison Mines Ltd.	Hr	Room and pillar	U, RE
Quirke-Panel	P[5]	Rio Algom Ltd.	Hr	..do	U, RE
Stanleigh	P[5]	..do	Hr	..do	U, RE
India:					
Chavara (IRE)	P	India Rare Earths Ltd. (IRE)	Pl	Strip level	R, I, L, Z, RE
Chavara (KMML)	P	Kerala Minerals and Metals Ltd. (KMML)	Pl	Dredge	R, I, L, Z, RE
Manavalakuruchi	P	IRE	Pl	Strip level	I, R, SR, Z, RE
Orissa-Chatrapur	Dev	..do	Pl	Dredge	R, I, L, Z, RE
Ranchi-Purulia*	Exp	Indian Government	Pl	Strip level	RE, I, Z, R, S
Malawi: Kangankunde*	Exp	Lonhro Ltd.	Hr	Open pit	RE
Republic of South Africa:					
Richards Bay	P[5]	QIT, Union Corp.; IDL	Pl	Dredge	S, R, Fe, Z, RE
Sri Lanka: Pulmoddai	P	Sri Lankan Government	Pl	Strip level	I, R, Z, RE
United States:					
Bear Valley	PP	Bear Valley Industries	Pl	Dredge	I, RE, G, C
Big Creek*	PP	Several	Pl	..do	RE, I, G, Z
Brunswick-Altamaha	Exp	Union Camp Corp.	Pl	..do	R, M, Z, RE
Gold Fork-Little Valley	Exp	Several	Pl	..do	I, Z, RE, Au, G
Green Cove Springs	P	AMC	Pl	..do	R, I, L, Z, RE
Mountain Pass*	P	Molycorp Inc.	Hr	Open pit	RE
Oak Grove	Exp	Ethyl Corp.	Pl	Dredge	I, R, Z, RE
Powderhorn	Exp	Buttes Gas and Oil Co.	Hr	Open pit	P, RE
Silica Mine	P[5]	Tennessee Silica Sand	Pl	..do	SS, I, R, L, Z, RE

[1]Properties that do or could produce REO as the primary product are identified with an asterisk.
[2]P = producer; PP = past producer; Exp = explored prospect; Dev = developing property.
[3]Pl = placer; Hr = hardrock.
[4]The first product listed was assumed to be the primary product for this study. Au = gold; C = columbium; Fe = magnetite; G = garnet; I = ilmenite concentrate; L = leucoxene concentrate; M = mixed ilmenite-leucoxene concentrate; P = perovskite concentrate; R = rutile concentrate; RE = REO concentrate; S = titanium slag; SR = synthetic rutile concentrate; SS = silica sand; Z = zircon concentrate; U = uranium.
[5]Producers that do not presently recover REO.

tain 477,000 mt, or 14% of the total recoverable REO in all properties evaluated. Titanium properties thus account for 43% of the total recoverable REO in all properties evaluated for this study.

Producers that recover REO-bearing minerals as the primary commodity contain 1,566,000 mt, or 47% of the total recoverable REO in all properties evaluated. Mountain Pass accounts for nearly the entire amount. Nonproducers that could recover REO as the primary product contain 337,000 mt, or the remaining 10% of total REO contained in all properties evaluated.

In terms of country totals (table 4), U.S. properties contain 1,994,000 mt recoverable REO, or 59% of the total in all properties evaluated. Mountain Pass accounts for nearly 80% of the U.S. total, and nearly half of the total in all properties evaluated. Australian properties, all of which do or could produce REO (primarily in monazite) as a byproduct of titanium mining, contain 303,000 mt REO, or about 9% of the total. Of the total amount of REO contained in Australian properties, producers account for 85%.

Brazilian properties account for only 15,000 mt recoverable REO, which is less than 1% of the total in all properties evaluated; producers account for 67% of total recoverable REO in Brazilian properties evaluated.

The three Elliot Lake, Canada, operations that could produce byproduct rare earths contain 14,000 mt recoverable REO, less than 1% of the total.

Properties in India and Sri Lanka contain 815,000 mt recoverable REO, or 24% of the total in all properties evaluated. Of this, the five producers, all primary titanium properties, account for 86% of the total.

Malawi and the Republic of South Africa contain a total of 214,000 mt recoverable REO, all from nonproducers. Richards Bay, in the Republic of South Africa, is a titanium producer that does not presently recover monazite.

Table 4.—Demonstrated rare-earth resources of evaluated properties, January 1984

Country and status	Number of properties	Ore treated, 10^6 mt	Feed grade, % REO	Recoverable REO, 10^3 mt
Australia:				
Producers	8	1,214	0.04	259
Nonproducers	5	1,218	.01	44
Total Australia	13	2,432	.03	303
Brazil:				
Producers	2	3	.43	10
Nonproducers	3	2	.34	5
Total Brazil	5	5	.39	15
Canada: Nonproducers	3	241	.01	14
India and Sri Lanka:				
Producers	5	553	.37	700
Nonproducers	1	86	.19	115
Total India and Sri Lanka	6	639	.35	815
Malawi and Republic of South Africa: Nonproducers	2	626	.07	214
United States:				
Producers	2	107	2.09	1,558
Nonproducers	7	876	.13	436
Total United States	9	983	.34	1,994
Grand total	38	4,926	.14	3,355

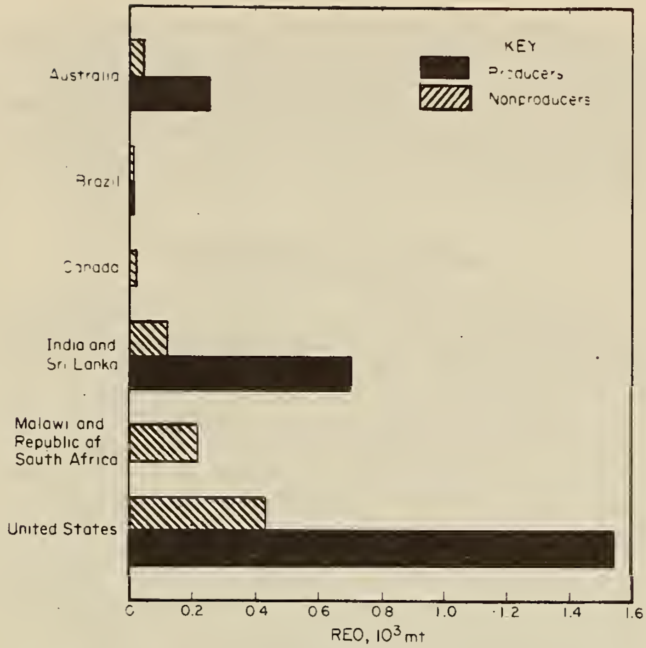

FIGURE 3.—Total recoverable REO, by country and property status.

MINING AND BENEFICIATION

MINING

Since commercial amounts of rare-earth-bearing minerals occur in placers, veins, and igneous intrusive complexes, mining methods include placer (predominantly dredging), open pit, and underground.

For heavy mineral operations recovering monazite as a byproduct, such as those in Australia and India, dredging is the most common mining method employed. Floating cutter-head dredges are the most common type of machinery used if the mineral sands are loose and occur at depths of less than 20 m. Preliminary concentrating occurs on the dredge, or on barges alongside, using Reichert cones, spirals, jigs, tables, and similar equipment.

Where floating dredges are not practicable (e.g., deposits that are several kilometers inland and where water is in short supply), or the size, shape, and lithology of the ore body are impractical for dredges, other mining methods are employed. Draglines, front-end loaders, and trucks are used in most cases.

The only producing open-pit hardrock operation evaluated for this study is Mountain Pass, where bastnasite ore is produced from a tabular carbonatite intrusive ore body. Kangankunde, an undeveloped hardrock property in Malawi, would probably also utilize open-pit mining methods.

The only underground operations evaluated for this study were the Elliot Lake district uranium mines in Ontario, Canada. There, room-and-pillar methods are used to extract uranium ore from quartz pebble conglomerates. Monazite occurs as a secondary mineral in the uranium ore.

BENEFICIATION

The Mountain Pass operation utilizes flotation to process the bastnasite ore. Kangankunde, the other hardrock property evaluated, would also use flotation methods. Initial concentration of placer sands occurs in wet mills, with final concentration and mineral separation in dry mills. In some cases, prior to wet concentration, ore goes through a feed preparation stage (to wash clay particles), which can include a number of separate processes depending on the amount of clay and throughput rate. A wet screening stage is used to prepare suitably sized feed for the wet gravity concentrator.

Wet mills can be land-based or floating. In a typical operation, ore from a dredge or slurry sump is pumped at 25% to 30% solids to the wet mill, where ore is fed into one or more stages of Humphreys spirals and/or Reichert cone concentrators, producing a preliminary heavy mineral concentrate. Rough, heavy mineral concentrate from the wet mill is transported, usually by truck or barge, to the dry mill for further processing.

Dry mills use various stages of magnetic, electrostatic, and gravity separation techniques to produce ilmenite, rutile, leucoxene, zircon, and monazite concentrates. The specific flowsheet of a dry mill depends on the type of ore and the heavy mineral assemblage to be recovered. In general, a dry mill separation process consists of high-tension electrostatic separators to separate conducting from nonconducting minerals. The relatively nonmagnetic monazite is separated from the more magnetic zircon fraction.

A unique beneficiation process was used at Denison Mines' Elliot Lake operation in Canada, where a Y_2O_3-REO concentrate was produced as a byproduct from the barren uranium solution. The process included leaching, solvent extraction, and precipitation to produce a 63.5% concentrate, of which Y_2O_3 is the major component, averaging 40% in the concentrate.

POSTMILL PROCESSING

Solvent extraction is the most important process used to separate the rare earths. The process is based on the different affinities of the rare-earth elements between a solution of rare earths in water and a chelating agent in an organic solvent. The stages involved in the production process are (1) chemical reduction, (2) removal of non-rare-earth elements, (3) fractionation of rare-earth mixtures, and (4) precipitation, calcination, and grinding. The procedure can include several stages; for example, Rhone-Poulenc's La Rochelle, France, chemical separation plant is equipped with more than 1,000 mixers-settlers to achieve the partition of the rare-earth elements. A comprehensive discussion of chemical separation techniques and processes is provided by Subbarao and Wallace (*10*).

One disadvantage of the solvent extraction technique is that operating costs for small-capacity units are high because the same number of personnel are required regardless of plant size. Consequently, the production of rare earths in small demand (e.g., holmium, erbium) is more costly than that for lanthanum or yttrium. Rhone-Poulenc uses a chromatographic ion exchange process using resins from small-scale rare-earth separations that do not warrant setting up a full-scale solvent extraction circuit (*11*).

PROCESSING INDUSTRY STRUCTURE

The rare-earth industries in Brazil, Malaysia, and India are to a large extent vertically integrated operations because the governments of those countries prohibit the export of monazite. Five European countries (France, the Federal Republic of Germany, Austria, Norway, and the United Kingdom) process rare earths. Japan has a large number of companies that process rare earths from all currently produced rare-earth-bearing mineral ores. In spite of its importance as the world's leading monazite producer, Australia presently has no rare-earth separation facilities. However, Allied Eneabba has announced plans to construct a plant to process 12,000 mt/yr monazite and 100 mt/yr xenotime (*12*).

Rhone-Poulenc of France is a major world REO processor. It processes both monazite and xenotime, but xenotime composes only about 1% of the raw material (*5*, p. 28). The company has a plant at La Rochelle on the French Atlantic coast, and in 1981 it opened a second production plant at Freeport, TX, with a planned production capacity of 4,000 mt/yr, which will effectively double the company's overall capacity when it reaches completion. The Freeport plant produces light rare-earth compounds from an intermediate rare-earth hydroxide concentrate, and the heavy rare-earth residue is sent to La Rochelle for final separation into high-purity rare earths. Most of the thorium produced in the process is sold in nitrate form for gas mantle manufacture and thorium metal production; however, a small quantity of ThO_2 is sold to the nuclear industries in several countries.

In the United States, Molycorp Inc., the world's largest producer of REO from its Mountain Pass operation, is a fully integrated company, producing rare-earth concentrates, compounds, and metals at its plants in York and Washington, PA, Louviers, CO, and at Mountain Pass, CA. In 1982, Molycorp started up an additional rare-earth separation circuit at its Mountain Pass complex for the production of samarium, gadolinium, lanthanum, praseodymium, and neodymium oxides.

In addition to Molycorp, an important U.S. rare-earth producer is the Davison Chemical Division of W. R. Grace and Co., which imports monazite from Australia to its plant at Chattanooga, TN, for the production of rare-earth chlorides. The chlorides are produced solely for internal use in the manufacture of petroleum cracking catalysts (*5*, p. 26). Two companies, Ronson Metal Corp. and Reactive Metals and Alloys Corp. (Remacor), produce mischmetal at processing plants in the United States.

Although this study is restricted to MEC countries, an important development in the rare-earth processing market has been the recent emergence of China as a major producer. The country has the world's largest reserves of contained REO, and since the 1970's it has become a major processor. The Yao Lung Chemical Plant in Shanghai can process and separate 2,000 mt/yr REO, primarily from monazite. Products available for export include phosphor preparations (e.g., Y_2O_3 and Eu_2O_3) and magnetic materials such as samarium and samarium-cobalt alloys (*5*, p. 24). The country exports to Europe, the United States, the Soviet Union, and Japan.

PRODUCTION COSTS

Operating costs and capital investments for the appropriate mining, milling, and transportation methods were obtained or estimated for each property evaluated. In most cases, actual costs were available from published material, company personnel, other persons familiar with the operation, or from confidential, unpublished studies.

Total operating cost is a combination of direct and indirect costs. Direct costs include production and maintenance labor, materials, payroll overhead, and utilities. Indirect operating costs include administration, facilities maintenance and supplies, research, and technical and clerical labor.

Capital expenditures were obtained or estimated for exploration, acquisition, development, and mine and mill plant and equipment. Capital expenditures for mining and milling facilities include the costs of mobile and stationary equipment, construction, engineering, infrastructure, and working capital.

Operating and capital costs for "typical" Australian heavy mineral sands operations are induded in a recent Bureau report (*13*). Mine and mill operating costs for evaluated properties are shown in table 5. Costs are weight-averaged on the basis of annual ore capacity. It would be meaningless to present operating costs in terms of REO product, since nearly all properties produce REO as a byproduct of titanium mining. In fact, for several properties, REO is a relatively minor byproduct in terms of total revenues.

Table 5.—Average mining and milling costs
(January 1984 U.S. dollars per metric ton ore)

Country and status	Mine	Mill	Total
Australia:			
Producers	0.77	0.40	1.17
Nonproducers	.74	.48	1.22
Brazil:			
Producers	1.82	1.85	3.67
Nonproducers	1.99	1.92	3.91
India and Sri Lanka:			
Producers	.53	1.28	1.81
Nonproducers	2.05	4.35	6.40
Malawi and Republic of South Africa:			
Nonproducers	.54	.62	1.16
United States:			
Producers	W	W	W
Nonproducers	.76	.81	1.57

W Withheld to avoid disclosing company proprietary data.

Mining and milling costs are not shown for the Elliot Lake, Canada, properties since they would use special leach, solvent extraction, and precipitation techniques to recover REO from a barren uranium solution. Only the costs associated with treating the barren uranium solution were included in this evaluation.

The weighted-average mine operating cost for the eight Australian producers is $0.77/mt, which includes three strip level mines and one open-pit mine averaging $1.91/mt, and four dredge operations averaging $0.48/mt. Since the costs are weight-averaged according to annual capacity, they are heavily influenced by the low unit costs at the North Stradbroke operation of Consolidated Rutile Ltd., which is expected to produce nearly 40 million mt/yr ore by the late 1980's. The average mill cost is $0.40/mt for all producers.

The five Australian nonproducers that could recover byproduct monazite have a weighted-average mining cost of $0.74/mt, and a milling cost of $0.48/mt ore. These figures are strongly influenced by the costs at Cooloola, which is a past producer that terminated production when the area became part of the Cooloola National Park. All but Jurien Bay-Cooljarloo would be dredge operations.

The four Indian producers and one Sri Lankan producer together have a weighted-average mining cost of $0.53/mt and a milling cost of $1.28/mt ore. The two Brazilian producers, Anchieta and Buena, both of which are strip level operations with relatively small capacities (40,000 to 80,000 mt/yr), have weighted-average mining and milling costs of $1.82/mt and $1.85/mt ore, respectively. The Brazilian nonproducers could be brought into production at comparable operating costs ($1.99/mt mine, $1.92/mt mill); however, the capital expense necessary to build the mill and develop the deposits, and especially the high transportation costs associated with shipping the concentrates to port or process plant in Sao Paulo (as much as 1,200 km distant) render the Brazilian properties relatively expensive in terms of the total cost of production. The same is true for the undeveloped Indian property, Ranchi-Purulia.

Only one large-scale rare-earth property, Mountain Pass, is operating in the United States; consequently, operating costs are not disclosed for U.S. producers. Because Mountain Pass is an open-pit operation in a hardrock deposit, the operating costs are high relative to those for heavy mineral sands mining operations; however, the deposit has a very high grade (12% bastnasite with 6% to 7% REO content) compared with that of mineral sands deposits, so that the operating costs in terms of recovered product are relatively low.

The weighted-average costs for the five U.S. nonproducers that are mineral sands deposits (Big Creek, Bear Valley, Gold Fork-Little Valley, Bruswick-Altamaha, and Oak Grove) are $0.76/mt for mining, $0.81/mt for milling. These costs are comparable with those for other world properties. However, costs of transporting concentrates to existing processing plants for titanium and rare earths would be sufficiently high, especially in the case of the Idaho deposits, to place them at a significant disadvantage relative to several other world properties. Transportation costs for the Idaho properties are four to eight times higher than those for the western Australia properties. Additionally, the Big Creek and Gold Fork-Little Valley (Idaho) deposits have multiple landowners, and the actual costs associated with developing a unitized operation are not known.

REO AVAILABILITY

Nine of the 38 properties evaluated for this study do or could produce REO as the primary product. Five of these properties (i.e., the Brazilian properties) would be considered to be titanium properties from a revenues standpoint, although they are or could be mined for monazite because of its thorium content.

Table 6 shows the distribution of revenues of the various commodities that are or could be produced at the properties evaluated in this study. Revenue figures were based on January 1984 commodity prices (table 7). Figures for the Elliot Lake, Canada, operations, which would produce REO as a byproduct of uranium processing, are not included in

Table 6.—Average percentage of revenues by mineral concentrate type
(Based on January 1984 market prices)

Country and status	Rutile	Ilemite	Zircon	Monazite and bastnasite	Leucoxene	Synrutile	Other
Australia:							
Producers	30	30	17	3	10	10	0
Nonproducers	54	17	16	3	10	0	0
Brazil:							
Producers	13	31	25	31	0	0	0
Nonproducers	5	41	9	45	0	0	0
India and Sri Lanka:							
Producers	28	30	6	7	1	28	0
Nonproducers	14	5	3	46	0	0	32
United States:							
Producers	19	7	17	49	8	0	0
Nonproducers	12	24	16	14	16	0	18

Table 7.—Market prices of mineral sand concentrates and associates minerals, January 1984

Commodity	Where applicable (f.o.b.)	Grade, %	Price, $/mt
Garnet	Mill	Abrasive	$ 10.00
Ilmenite concentrate	Mill, Australia	[1]54+ TiO_2	32.00
	Mill, United States	[1]54+ TiO_2	42.00
Leucoxene concentrate	Mill, Western Australia	87 TiO_2	225.00
Magnetite	Mill	NAp	23.00
Monazite concentrate	Mill	55 REO	389.00
Rutile concentrate	Mill	95 TiO_2	347.00
Synthetic rutile	Plant, Mobile, AL, United States.	90+ TiO_2	350.00
Titanium slag	Sorel, Quebec, Canada.	71 TiO_2	159.00
	Richards Bay, Republic of South Africa.	85 TiO_2	181.00
Zircon concentrate	Mill, Australia	65 ZrO_2	104.50
	Mill, United States	65 ZrO_2	182.00

[1]Price does vary on TiO_2 grade (from approximately 47% to 64% TiO_2).

table 6, as only the marginal costs of REO recovery were included in the evaluation. However, Y_2O_3-REO concentrate production would account for less than 1% of the total revenues from the Elliot Lake operations.

Only Mountain Pass derives its total revenues from REO; therefore, the economic condition of the property is singularly dependent on the REO market. Because of the byproduct status of monazite, most properties included in this evaluation depend largely on the titanium market for their economic health. Australian producers on average derive only 3% of their revenues from monazite. Similarly, Indian and Sri Lankan producers on average derive only 7% of revenues from monazite.

TOTAL AVAILABILITY

Table 8 shows the cumulative total amount of potentially recoverable REO from all properties evaluated as a funtion of DCFROR. Figure 4 shows total potential availability by property status (producer and nonproducer), categorized by DCFROR range.

Only 21% (about 705,000 mt) of the total recoverable 3,355,000 mt REO in all properties evaluated is contained in properties that could not realize a positive DCFROR at the January 1984 market prices for commodities that are or could be produced from those properties. Nearly 77% (2,578,000 mt) of total recoverable REO in all properties evaluated is contained in producing properties. A logical supposition is that the majority of these properties are operating because they can consistently produce at a profit. A notable exception is the Brazilian operations, which are owned by NUCLEMON, a Government entity that has motives other than immediate profit or benefit (i.e., the need for thorium produced as a result of monazite processing).

Table 8.—Cumulative total REO potentially available from 38 evaluated deposits
(Thousand metric tons)

DCFROR, %	Producers	Nonproducers	Total
□90	1,910	0	1,910
□40	1,965	0	1,965
□20	2,135	35	2,170
□10	2,189	65	2,254
□ 0	2,526	126	2,652
• 0	702	1	703
Total	3,228	127	3,355

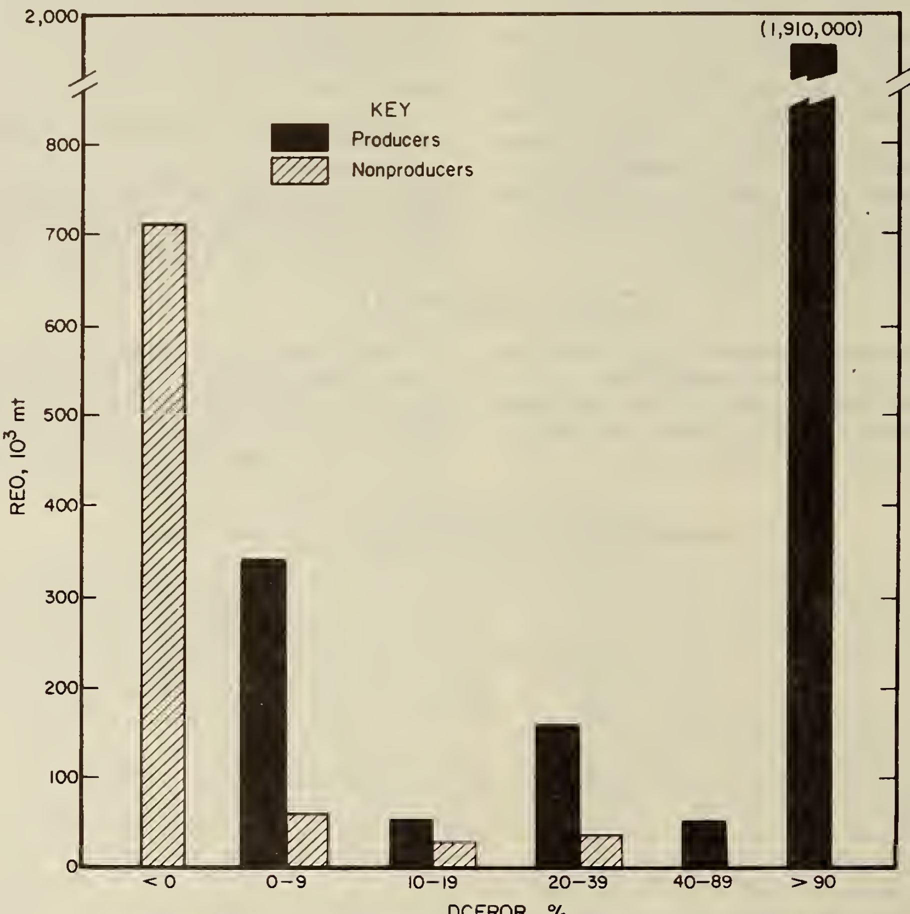

FIGURE 4.—Total recoverable REO, by property status and DCFROR.

About 126,000 mt, or less than 4% of the total REO in all properties analyzed, is contained in nonproducing proprties that could realize a positve DCFROR. Included here are the Silica Mine and Richards Bay properties, which are producing operations that are not presently recovering monazite but for which the costs of recovering monazite were included.

ANNUAL AVAILABILITY

Figures 5 and 6 present the amount of REO potentially available on an annual basis from producing and nonproducing properties at various DCFROR ranges. Since the general approach for this study was to evaluate the properties at their production capacity over the life of each property, the annual curves present total potential availability for each year shown and should not be interpreted as an assessment of future supply.

The total amount of REO potentially available annually from all producing properties (fig. 5) ranges from a low of 46,500 mt in 1986, to a peak of 51,500 mt in 1988-92, and declines to 49,900 mt by the year 2000. The increase between 1986 and 1988 is due to planned expansions that were included in the evaluation. Of the total amount potentially available in each year shown, only 6,600 mt is contained in properties that would not receive at least a 20% DCFROR. Total MEC production in 1984 was estimated at 40,700 mt (table 2). Clearly, the amount of REO potentially available from producing properties evaluated in this study (which represent 98% of total MEC production potential) is sufficient to sustain present production levels through at least the end of this century.

Figure 6 shows potential annual availability from nonproducers on a country basis. Australian and U.S. properties that could produce at positive DCFROR's together could provide only about 4,000 mt/yr REO through the year 2000. U.S. nonproducers evaluated that could not presently realize a positive DCFROR could provide 9,500 mt/yr REO over the same period; Australian nonproducers in the same category could sustain an annual output of 3,700 mt only for a few years, after which these properties could provide less than 1,000 mt/yr. Nonproducers in India and Malawi could account for a combined output of 9,200 mt/yr through

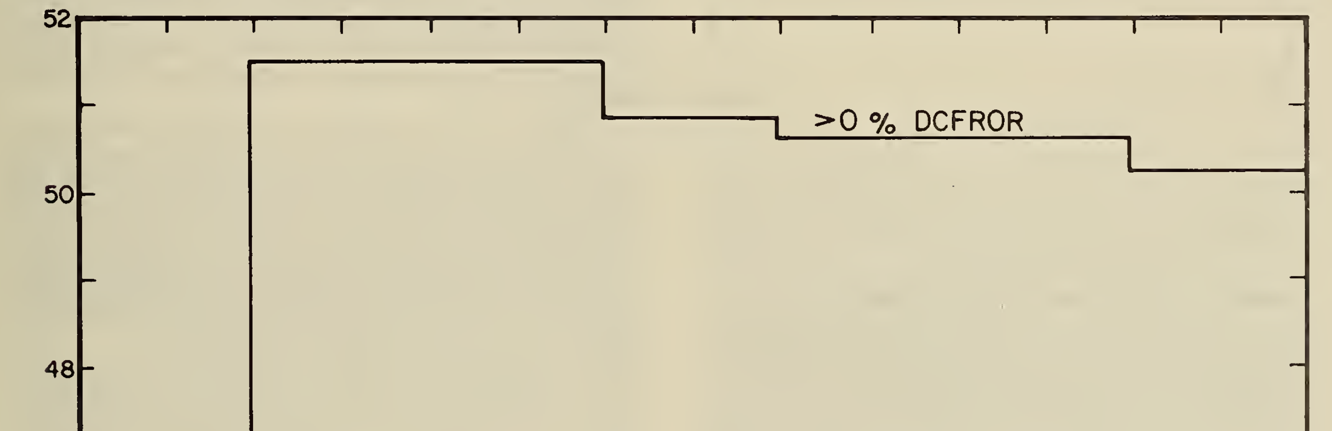

FIGURE 5.—Cumulative potential annual REO availability, producers.

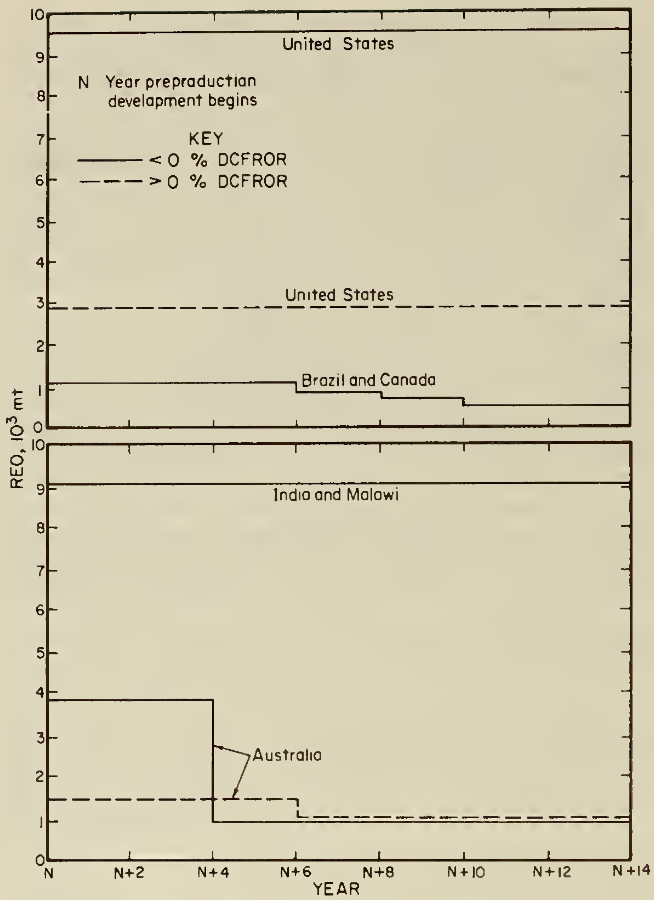

FIGURE 6.—Potential annual REO availability, producers.

the year 2000. Most of this production (India and Malawi) would be from the Ranchi-Purulia deposit in India.

Obviously, the amount of REO potentially available on a total and an annual basis from nonproducers largely depends on the number and character of undeveloped deposits analyzed for this study. Resource information for REO properties worldwide is difficult to obtain, since rare earths are used in highly advanced technological applications, and historical demand has been relatively small compared with demand for other mineral commodities. Furthermore, demand has been fulfilled by a relatively small number of properties, most of which (e.g., Australian operations) produce small amounts of REO minerals that make a relatively insignificant (byproduct) contribution to the revenues of titanium operations. Only Mountain Pass is an operation that is important as a producer of REO exclusively, and it did not become a prominent producer until the mid-1960's, when demand for REO began to increase at a substantial rate. The industry in many ways can be considered to be in its infancy, and demand should continue to increase as more uses are found for rare earths that are currently in demand, and new applications are developed for several that currently have no known commercial uses.

AVAILABILITY OF INDIVIDUAL REO, Y_2O_3, AND ThO_2

Table 9 shows the total amount of individual REO, Y_2O_3, and ThO_2 contained in concentrate from the evaluated properties, by country and property status. The figures are only approximate, since they were derived using estimated average REO, Y_2O3, and ThO_2 grades of monazite and bastnasite concentrates. ThO_2 content of monazite from the various countries were obtained from a 1971 Bureau report (*14*). Typical ThO_2 content of monazite from important sources is 7.0% from Australia, 6.5% from Brazil, and 8.5% from India.

Because of the composition of bastnasite, which, compared with monazite, contains a higher percentage of the light rare earths (lanthanum through europium), U.S. producers (largely Mountain Pass) account for nearly half (48%) of total REO in all properties evaluated. U.S. producers account for a small percentage of the heavy REO (including Y_2O_3) because bastnasite contains smaller amounts of the heavy oxides than monazite, the REO ore mineral in all properties evaluated except Mountain Pass.

The important yttrium-bearing mineral xenotime, which contains 60% Y_2O_3, only occurs in economic quantities in one of the properties evaluated (Capel, Australia). Xenotime is produce as a byproduct of tin mining in Malaysia and Thailand. Were this evaluation to have included properties that do or could produce xenotime, the amount of Y_2O_3 potentially available would be somewhat larger than the figures shown.

Table 9.—Individual REO, Y_2O_3, and ThO_2 contained in evaluated properties
(Metric tons)[1]

Country and status	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y	Th
Australia:																
Producers	59,570	119,140	12,950	49,210	7,770	260	4,400	410	1,300	230	340	30	160	20	5,180	25,900
Nonproducers	10,120	20,240	2,200	8,360	1,320	40	750	70	220	40	60	—	30	—	880	4,400
Brazil:																
Producers	2,300	4,600	500	1,900	300	10	170	20	50	10	10	—	10	—	200	1,000
Nonproducers	1,150	2,300	250	950	150	10	90	10	30	10	10	—	—	—	100	500
Canada: Nonproducers	140	140	240	140	310	260	710	260	1,420	350	920	120	450	100	9,440	—
India and Sri Lanka:																
Producers	161,000	322,000	35,000	133,000	21,000	700	11,900	1,120	3,500	630	980	70	420	40	14,000	70,000
Nonproducers	26,450	52,900	5,750	21,850	3,450	120	1,960	180	580	100	150	10	70	10	2,300	11,500
Malawi and Republic of South Africa: Nonproducers	49,220	98,440	10,770	40,660	6,420	210	3,640	340	1,070	190	280	20	130	10	4,280	21,400
United States:																
Producers	498,560	779,000	62,320	202,540	7,790	1,560	2,340	—	10	—	—	—	—	—	1,560	230
Nonproducers	100,280	200,500	21,800	82,840	13,080	440	7,410	700	2,680	390	570	40	260	30	8,720	43,600
Total	908,790	1,599,320	151,710	541,450	61,590	3,610	33,370	3,110	10,860	1,950	3,320	290	1,530	210	46,660	178,530

[1]Rounded to the nearest 10 mt.

CONCLUSIONS

There are sufficient resources of rare earths in producing deposits to sustain present production levels at least through the end of the century, and probably well beyond. However, because of the byproduct status of monazite from several important producing properties, the supply of some of these elements depends largely on the titanium market. Should the titanium market become unfavorable to heavy mineral sands producers, the amount of many of the heavy rare earths available for processing could be a matter of some concern.

The availability and supply of the light rare earths, which are relatively abundant in the mineral bastnasite, are assured because of the Mountain Pass, CA, operation, which accounts for about half of total annual world production of REO. The deposit has sufficient resources to last for many years and, given favorable future demand, should continue to be a viable operation for the forseeable future.

Production of xenotime provides for additional supplies of the heavy rare-earth elements, particularly yttrium, which occurs in a concentration of 25% to 30% Y_2O_3 in xenotime and for which the mineral is recovered. However, xenotime recovered as a byproduct of tin mining in Malaysia and Thailand presently accounts for a minor percentage (probably less than 1%) of total world rare-earth production. Consequently, the availability of yttrium depends largely on the tin market. However, the recent discovery of potentially important yttrium deposits in Canada (Thor Lake and Strange Lake), and the possibility of recovery of yttrium at the Elliot Lake operations, suggests that the potential availability of yttrium is reasonably assured.

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APPENDIX.—PROPERTY DESCRIPTIONS

AUSTRALIA

In 1984, heavy mineral sands operations in Australia produced 9,000 mt REO, second only to Molycorp's Mountain Pass, CA, operation, whose 25,000 mt of output accounted for essentially all of U.S. production. Australia is the world's largest producer of monazite, which is recovered as a byproduct of rutile, ilmenite, and zircon mining from beach sand deposits on the east and west coasts of the country.

In recent years, more monazite has been produced on the west than the east coast because of increased production of heavy mineral sands from that area. This shift is due to a general decline in heavy mineral sands reserves on the east coast, environmental legislation that has prevented mining of some reserves, and the emergence of Allied Eneabba Ltd., now the country's largest heavy mineral sands producer, on Australia's west coast. Monazite production from the west coast nearly doubled from 1977 to 1978, accounting for 84% and 98%, respectively, of total Australian monazite production in those years (*5*, p. 20).

Heavy mineral deposits on Australia's east coast occur along 1,700 km of coastline. Five east coast Australian properties containing REO were evaluated for this study (fig. A-1). They include the past producers Cooloola, Fraser Island, and Munmorah, and two producing properties on North Stradbroke Island, one owned by Consolidated Rutile Ltd. (CRL), the other by Associated Minerals Consolidated Inc. (AMC). Together, the five properties contain more than 37,000 mt recoverable REO, all in monazite. The producers recover rutile as the primary titanium product and account for more than 14,000 mt recoverable REO.

It is unlikely that the Fraser Island or Cooloola deposits, although past producers, will be exploited again in the near future. Mining has been banned from Fraser Island since 1976, when, because of environmental concerns, the Australian Government revoked export licenses for operations that produced minerals there. The Cooloola property was included within the Cooloola National Park when it was formed by legislative decree in 1974. Nevertheless, the deposits contain potentially available, recoverable amounts of monazite, so the properties were included in this evaluation.

Of the two North Stradbroke Island operations, only the one owned by CRL, which has been in production since 1967, has produced and marketed monazite. The company first reported monazite production in 1980, with recovery of a few hundred metric tons. Recovery of monazite has never been reported from the AMC operation, and the company evidently has no current plans to do so in the future.

Eight REO-bearing heavy mineral properties on Australia's west coast were included in this evaluation (fig. A-2): Allied Eneabba, Cable Sands, Capel, Cataby, Eneabba, Jurien Bay-Cooljarloo, North Capel, and Yoganup Extended. All but Cataby and Jurien Bay-Cooljarloo were producing at the time of this evaluation. Together, the eight properties contain about 266,000 mt recoverable REO, of which the Allied Eneabba property accounts for more than half. The six producers account for nearly 245,000 mt, or about 92% of the total recoverable REO in west coast properties evaluated.

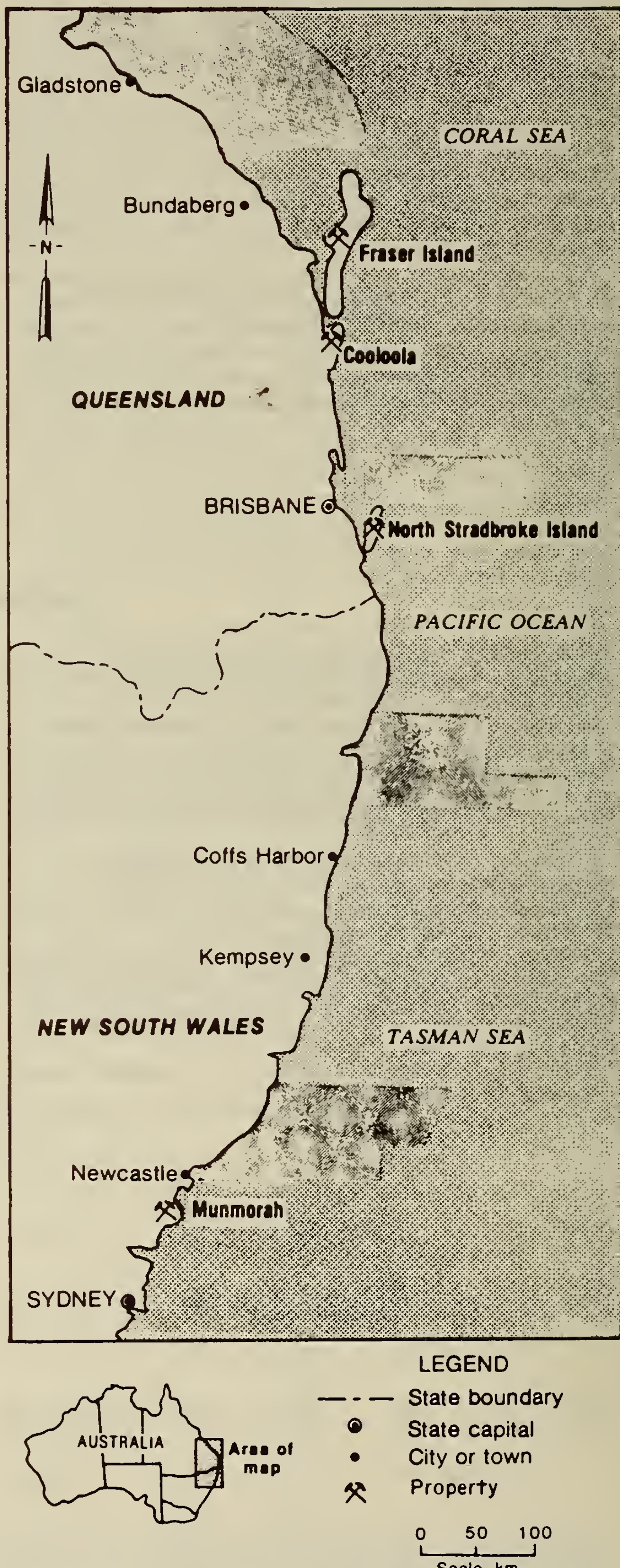

FIGURE A-1.—Location map, Australian east coast properties.

[1]Italic numbers in parentheses refer to items in the list of references preceding the appendix.

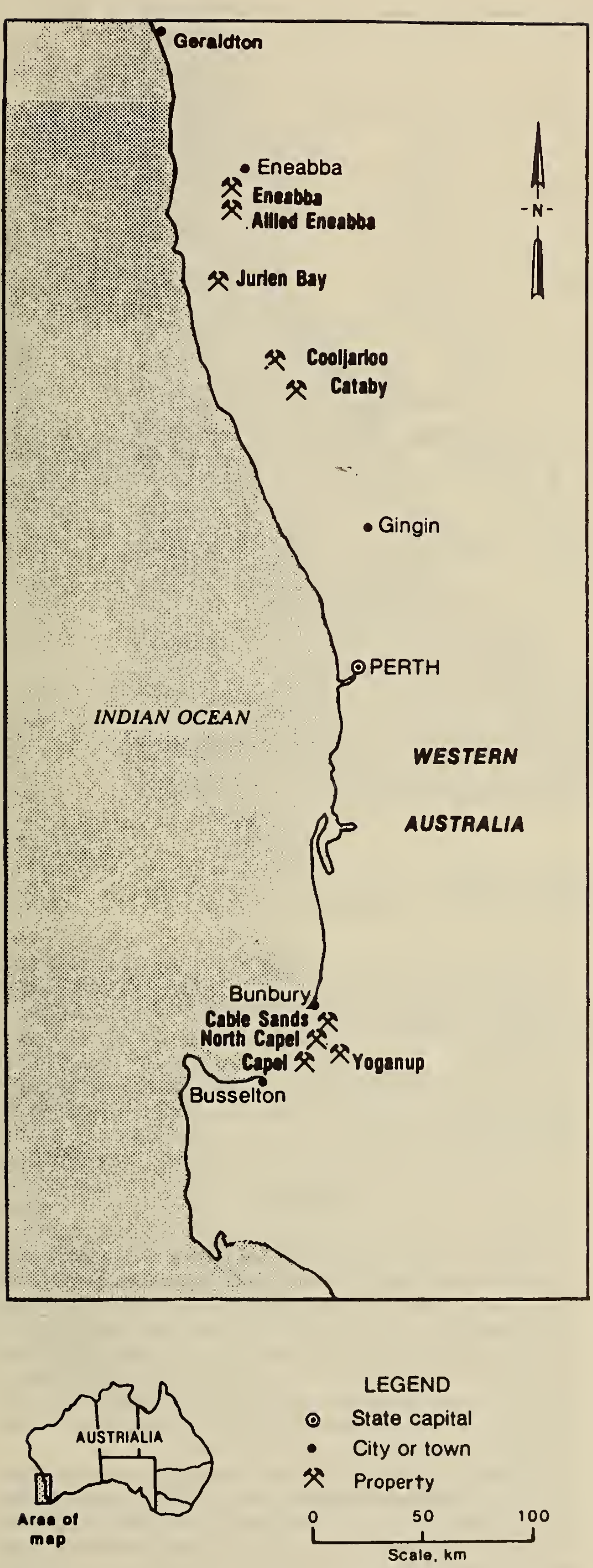

FIGURE A-2.—Location map, Australian west coast properties.

Allied Eneabba Ltd., affiliated with E. I. du Pont de Nemours and Co., Inc., has emerged as an important producer in the world REO market since the mid-1970's. Monazite accounts for about 10% of Allied Eneabba's total revenue, although it is only 3% of the company's total volume. Eneabba undertook a major expansion program at its Narngulu dry separation plant at Geraldton, Western Australia, in 1980, increasing capacity by 30%. The Allied Eneabba operation produced 10,440 mt monazite (nearly 6,000 mt REO) in 1983. The previous year, only 5,704 mt monazite were recovered, indicating the erratic distribution of monazite in the deposit. In 1981, reserves in lands adjacent to the Eneabba operation were outlined, extending the mine's life to 28 years (*5*, p. 20).[1]

Associated Minerals Consolidated Ltd. (AMC) is the second largest producer of REO minerals in Australia, with an annual production of 2,800 mt monazite from its Capel and Eneabba operations in Western Australia. The Eneabba operation has a capacity of 2,000 mt/yr monazite. Capel currently has a capacity of 800 mt/yr, plus a small amount (6 to 15 mt/yr) of xenotime (*5*, p. 21).

Yoganup Extended (owned by Westralian Sands Ltd.) has an annual output of about 2,000 mt monazite, which typically constitutes 5% of the heavy mineral concentration in the beach sand. The Cable Sands property of Cable Sands Pty. Ltd. can produce up to 1,000 mt/yr monazite and 50 to 60 mt/yr xenotime from beach sands near Koombana Bay near Bunbury. Typically, the operation produces between 500 and 1,000 mt/yr monazite (*5*, p. 21).

In spite of its importance as the world's second largest REO producer and leading supplier of monazite, Australia presently exports all of its production because it has no postmill processing facilities. However, Allied Eneabba Ltd. recently proposed to construct a plant to recover rare earths from concentrate. The plant, to be located at Geraldton, Western Australia, would process 12,000 mt/yr monazite concentrate and 100 mt/yr xenotime concentrate. Among rare earths to be produced are samarium, europium, gadolinium, terbium, and yttrium. (*12*).

BRAZIL

Brazil mines heavy mineral sands for its monazite content, although from a recovered-value standpoint, the titanium minerals are the most valuable constituent. The country prohibits the export of monazite because of its thorium content, and processes its monazite within the country. The industry is controlled by Empresas Nucleares Brasileiras S.A. (commonly known as NUCLEBRAS), a Government-owned entity that was formed in 1974. Mining operations are conducted by Nuclebras de Monazita e Associados Ltda., known as NUCLEMON, a Government-owned subsidiary.

Brazil's present capacity is 3,000 mt/yr monazite at NUCLEMON's processing plant in Sao Paulo. The country produced an estimated 2,000 mt monazite concentrate in 1984, or approximately 1,100 mt contained REO. Annual production of REO has been at approximately this level since at least the late 1970's.

Brazilian properties evaluated for this study include Alcobaca, Anchieta, Aracruz, Buena, and Serra (fig. A-3). Anchieta and Buena were producing at the time of this evaluation. Total recoverable REO in the five properties is approximately 15,000 mt. All of the properties are on Brazil's Atlantic Ocean coast, where heavy minerals have been concentrated in the beach environment.

FIGURE A-3.—Location map, Brazilian properties.

Initial (wet plant) concentration for nonproducers probably would be done onsite, as is presently done at the two producing operations (Anchieta and Buena). There is a dry plant at Guarapari, where concentrate from the wet plant at Anchieta, 10 km distant, is processed. The plant was temporarily closed in January 1982 for expansion. Buena concentrate is processed at a nearby dry plant.

Development of the Alcobaca property would require construction of a dry plant nearby. Concentrate produced at Aracruz, another undeveloped deposit, could be transported to the dry plant at Guarapari, some 100 km distant, as could concentrate from Serra, 60 km from Guarapari. For this evaluation, ilmenite and rutile from all operations were assumed to be transported to port at Vitoria, some 50 km away from the Guarapari dry plant. In all cases, monazite and zircon concentrate produced at the dry plants are (in the case of Anchieta and Buena) or would be transported to Brazil's hydrometallurgical plant at Sao Paulo, 800 km from Guarapari.

In spite of the transportation requirements, and the relatively small amount of contained REO in Brazilian properties compared with that in other world deposits (e.g., those that produce monazite as a byproduct of titanium mining in Australia and India), the Brazilian Government appears committed to production of monazite, largely because of its thorium content.

CANADA

Three Canadian properties at Elliot Lake, ON, were evaluated for this study (fig. A-4). They include Rio Algom Ltd.'s Quirke-Panel and Stanleigh Mines, and the property of Denison Mines Ltd., all of which would produce REO and Y_2O_3 byproducts of uranium processing. Denison Mines first started investigating the recovery of Y_2O_3 and REO in the mid-1960's, and produced a total of about 100 mt from 1974 through 1976. The plant produced a concentrate that graded approximately 40% Y_2O_3 and 23% REO.

Neither company presently has plans to recover REO or Y_2O_3, but these commodities were evaluated to determine their additional cost of recovery from, and potential availability in, the barren solution now produced by the uranium operations.

Highwood Resources Ltd. recently announced the discovery of commercially significant quantities of yttrium

FIGURE A-4.—Location map, Canadian and U.S. properties.

at its Thor Lake beryllium prospect near Yellowknife, NT. On the basis of preliminary assays, it is estimated that the deposit contains 3,600 mt Y_2O_3, sufficient to supply current world demand for yttrium for about 7 yr. Since information sufficient to perform an evaluation was not available at the time of this study, the Thor Lake property was not included.

The Strange Lake deposit, located on the Quebec-Newfoundland border in northeastern Canada, was discovered in 1979. The deposit occurs within an alkaline complex and contains columbium, fluorite, zirconium, beryllium, and yttrium-rich rare earths. At the time of this evaluation, resource data were insufficiently known to allow for detailed analysis. Iron Ore Co. of Canada is pursuing further exploration and metallurgical studies on its property, which, if developed, could be an important source of Y_2O_3 and REO.

INDIA

Five Indian properties were evaluated for this study, only one of which (Ranchi-Purulia, an undeveloped property) has the resources to produce rare earths as the primary product. The others, all producers, recover monazite as a byproduct of processing titanium minerals. These include two properties at Chavara, one at Manavalakuruchi, and one at Orissa-Chatrapur (fig. A-5). Together, the five properties contain more than 812,000 mt recoverable REO, of which more than 85% is contained in the four properties that produce monazite as a byproduct of titanium mining.

The country produced an estimated 2,200 mt REO in 1984 (table 2), most of which was shipped to the United States. Two companies, Indian Rare Earths Ltd. (IRE) and Kerala Minerals and Metals Ltd. (KMML), are responsible for all Indian production. IRE is a public company operated by the Indian Government; KMML is operated by the state government of Kerala. India prohibits the export of monazite because of its thorium content, based on thorium's future use as a nuclear fuel.

IRE's mines on the west coast of India at Chavara near Quilon, and Manavalakuruchi in Tamil Nadu State, account for all of that company's monazite production. The company's separation plant in Kerala State currently has an operating capacity of 4,600 mt/yr rare-earth chlorides, 78 mt/yr rare-earth fluorides, and 60 mt/yr of individual REO. About 5,000 mt/yr trisodium phosphate is produced as a byproduct. IRE produces four grades of cerium oxide (CeO_2) and reportedly has plans to produce yttrium, gadolinium, europium, and samarium concentrates. IRE produces 110 mt/yr thorium nitrate, small amounts of ThO_2, and thorium pellets. The company recently began testing and partial operation of a new processing plant in Orissa, with a monazite processing capacity of 4,300 mt/yr. The plant will also produce synthetic rutile (*5*, p. 22; *12*).

KMML's mineral separation plant at Chavara (near Quilon in Kerala State) treats heavy mineral sands that are recovered from nearby deposits. Monazite constitutes

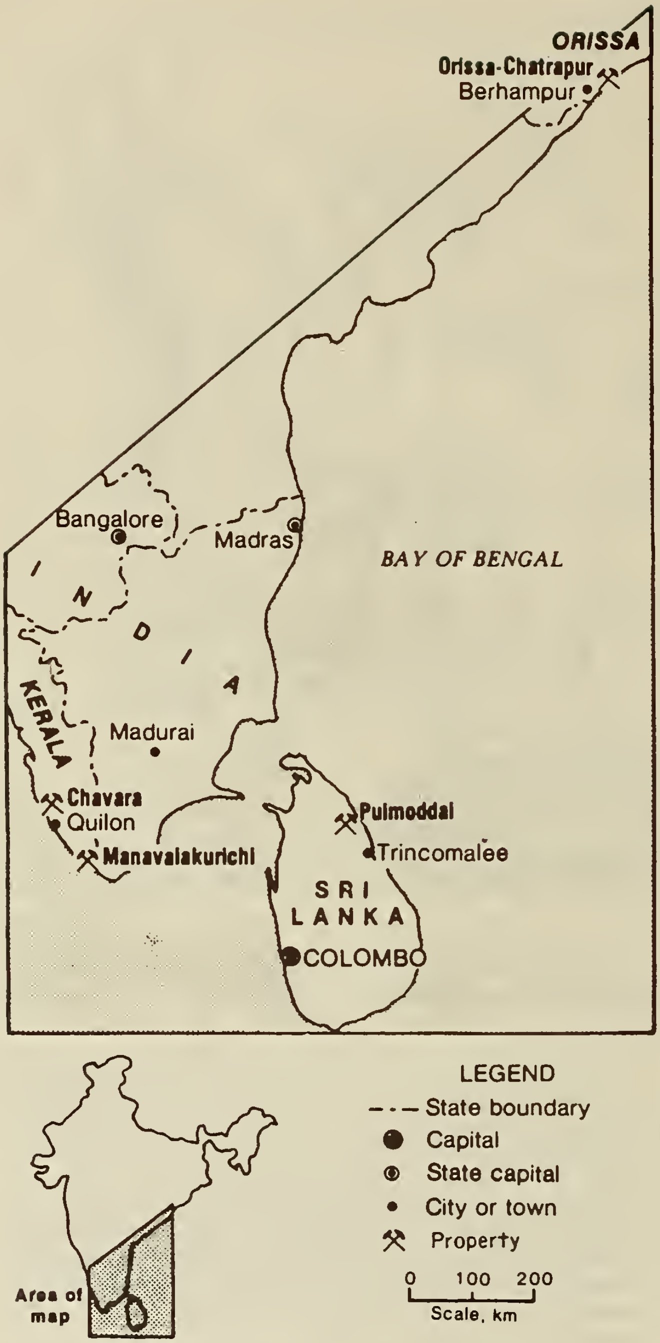

FIGURE A-5.—Location map, Indian and Sri Lankan properties.

1% of the 18% heavy mineral content of the sand. KMML's present production capacity is about 300 mt/yr monazite, but the company has plans to establish a new plant with a capacity of 1,800 mt/yr monazite by 1987.

The Ranchi-Purulia deposit, located in Bihar and West Bengal States 200 km northwest of Calcutta (not shown in fig. A-5), is more than 1,000 km from India's processing plants in the southern part of the country. For this evaluation, it has been assumed that a beneficiation plant (with a capacity of more than 5,000 mt/yr REO in a monazite concentrate) would be constructed near the deposit, from which five separate concentrates (monazite, ilmenite, rutile, zircon, and sillimanite) would be shipped by rail to port at Calcutta, from which the monazite would be shipped for further processing in southern India.

A new mineral sands deposit containing ilmenite, zircon, garnet, and monazite was recently discovered in the coastal beach of the Thanjavar district of India, between Sirkali and the mouth of the Cauvery River, near Kaveripattenan. Preliminary analyses showed a higher mineral content than for the Manavalakuruchi deposit. Reserves have not been determined, but it has been reported that the deposit's monazite content is at least equal to Manavalakuruchi's (*15*). The property was not included in this evaluation owing to the lack of sufficient cost and resource data.

MALAWI

The Kankankunde deposit, part of the Chilwa carbonatite complex in Malawi, has been under investigation since the early 1970's by Lonhro Ltd., the property's current owner. If developed, the property would be mined by open pit, treating a relatively high grade monazite ore. High iron content of the ore has necessitated special metallurgical testing, which resulted in the development of a workable process flowsheet in 1982.

Political problems in neighboring Mozambique, through which the monazite concentrate could be shipped, have resulted in postponement of the property's development. An alternative transportation plan, assumed for this evaluation, involves transport by truck and rail to port at Durban, Republic of South Africa.

MALAYSIA, SRI LANKA, AND THAILAND

Malaysia produced about 2,600 mt REO in 1984, nearly all of which was from monazite, with a small amount (probably less than 5%) from xenotime, the high-grade yttrium mineral. Malaysian rare-earth production is a byproduct of processing the tin mineral cassiterite. Beh Minerals Sdn. Bhd. has an ore concentrating plant at Lahar, in the State of Perak. Malaysian Rare Earth Corp. Sdn. Bhd. (MAREC), a joint venture between Beh Minerals and Mitsubishi Chemical Industries Ltd., has produced yttrium concentrate containing 60% Y_2O_3 since 1976; present production capacity is 80 mt/yr concentrate. At the time of this evaluation, information regarding REO grades of Malaysian tin properties was not available; consequently, no Malaysian properties were included in this study.

Monazite-bearing heavy minerals sands are located in Sri Lanka, most notably the Pulmoddai property (fig. A-5), which was evaluated for this study. Monazite production is a byproduct of titanium mining and is generally quite small, although 1982 production rose to 304 mt (*5*, p. 26).

Thailand is a potential monazite and xenotime producer as a byproduct of recovering tin ore. Thai production is generally sporadic, but reached 162 mt monazite and 46 mt xenotime in 1982. The country exports mainly to Japan and Europe.

REPUBLIC OF SOUTH AFRICA

At Richards Bay in the Republic of South Africa, Richards Bay Minerals recently commissioned a monazite extraction plant to recover the mineral as a byproduct of

titanium production. At the time of this evaluation (January 1984), detailed information was not available regarding the recovery operation, and the property was classified as a nonproducer of rare earths.

UNITED STATES

U.S. production of REO in bastnasite was 25,311 mt in 1984, all of which was obtained from Molycorp Inc.'s deposit at Mountain Pass, CA (*8*). Production of REO from monazite properties is not readily available but was estimated to be on the order of 1,000 mt in 1982 (*5*, p. 24). U.S. properties evaluated for this study include: Mountain Pass, CA; Bear Valley, ID; Big Creek, ID; Gold Fork-Little Valley, ID; Brunswick-Altamaha, GA; Green Cove Springs, FL; Oak Grove, TN; Powderhorn, CO; and Silica Mine, TN (fig. A-4). Mountain Pass is the only bastnasite property evaluated, and only Mountain Pass and Big Creek have REO as the primary product. Only Mountain Pass and Green Cove Springs currently produce rare-earth minerals. Silica Mine produces only silica sand, although the deposit contains recoverable amounts of heavy minerals, including monazite.

The total amount of recoverable REO from all U.S. properties is nearly 2 million mt, of which more than 75% is contained in Mountain Pass and nearly 15% in the undeveloped Powderhorn deposit in Colorado.

The Mountain Pass carbonatite reserves have been reported to be 36 million mt of ore grading 12% bastnasite (*5*, p. 25). The deposit is the world's largest producer of REO, typically accounting for nearly half of total annual world production. Molycorp is a fully integrated company, with rare-earth processing facilities at York and Washington, PA; Louviers, CO; and Mountain Pass, CA. The Mountain Pass facility produces three standard bastnasite concentrates grading 60%, 70%, and 85% contained REO.

Powderhorn is a large carbonatite-alkalic stock complex, owned by Buttes Gas and Oil Co., and located in Gunnison County, CO. The deposit was reported to contain 419 million mt identified resources, of which 271 million mt is demonstrated (*16*). Average grade is 12% TiO_2 in perovskite, which also contains rare earths. Based on the proposed production level of nearly 4 million mt/yr ore, an open-pit operation could produce more than 4,500 mt/yr of contained REO.

Green Cove Springs, the only U.S. producer of monazite evaluated in this study, is a mineral sands property that was acquired by AMC Ltd., a subsidiary of Renison Goldfields Ltd., in 1980. The company also owns the Eneabba and Capel properties in Australia. The Green Cove Springs operation had ceased production in 1978 under previous ownership by Titanium Enterprises, but monazite continued to be recovered from reprocessed tailings until mining restarted. The operation has a present capacity of 700 mt/yr monazite, or 400 mt/yr REO (*5*, p. 21).

The Bear Valley, Big Creek, and Gold Fork-Little Valley heavy mineral sands properties all occur in the same general region of west-central Idaho, adjacent to the Idaho batholith, a large igneous intrusion from which the minerals were derived. Mineral sands deposits in Long Valley and Bear Valley were dredged during the 1950's for monazite; ilmenite, garnet, zircon, columbite, and the radioactive minerals euxenite and samarskite were also recovered.

Although there are extensive mineral sands deposits in the west-central Idaho region, it is unlikely that development will occur in the near future. A portion of the Gold Fork property has been inundated by the Cascade reservoir, and extensive mining in Bear Valley would be a matter of environmental concern owing to its close proximity to a wilderness area. Nevertheless, the area was mined in the past and contains significant amounts of potentially important rare-earth minerals.